

# WRF Dynamically Downscaled Simulation of Projected Climate in the Missouri River Watershed: 2000–2050

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## 1. INTRODUCTION

General Circulation Models (GCMs) have been used to improve our understanding of the complex interactions of the earth system and provide increasingly realistic and useful predictions of future climate (IPCC, 2007; Edwards, 2011). Issues of scale and the hydrostatic assumption limit the ability of GCMs to simulate effects of regional topographic features and smaller-scale processes such as convective precipitation (CCSP, 2008; Salathé et al., 2010). Statistical downscaling (Hijmans et al., 2005; Schmidli et al., 2006; Stamm and Gettleman, 1995) and dynamical regional climate models (RCMs; Lo et al., 2008; Hostetler et al., 2011) have been developed to resolve features important at the regional and local scales.

This paper presents the use of the Weather Research and Forecasting Model (WRF) as a regional climate model to simulate projected climate for North America at a 36-km resolution forced by GCM output for the A2 emissions scenario (Nakićenović and Swart, 2000) for water years 2001–50 (a water year (WY) is the 12-month period, October 1 through September 30, and is designated by the calendar year in which it ends).

WRF output is summarized for the U.S. portion of the Missouri River watershed, the Yellowstone River watershed, and the James River watershed. WRF output is validated by comparison with PRISM output (Precipitation-Regressions on Independent Slopes Model; described by Daly et al., 1994, 2002) for water years 2001–11 using surface air temperature and total precipitation. Over the past 50 or more years, the Yellowstone and James Rivers have been exhibiting downward and upward trends in flows, respectively (Anderson and Norton, 2007). Analyses of WRF simulations of climate in these watersheds may provide a more complete understanding of these systems and expected trends in climate for the upcoming century.

## 2. METHODS

### 2.1 Domain Extent

Climate for WY 2001–50 using WRF (version 3.3.1; Wang et al., 2011) was simulated using a 36-km grid spacing over a domain that included the conterminous United States, Canada, and Mexico (fig. 1). The main area of interest for climate solutions was the Missouri River watershed. As such, domain extent was chosen to provide a sufficient buffer between the Missouri



**Figure 1.** Study area domain and watershed boundaries for presented results.

River watershed and lateral boundaries and to allow mesoscale circulation features to develop prior to reaching the Missouri River watershed.

### 2.2 Initial and Boundary Conditions

Boundary and initial conditions were based on the A2 emissions scenario experiment b30.042e of the Community Climate System Model version 3 (CCSM3; Collins et al., 2006) for August 2000 through September 2050. The first two months of simulation were used to allow the model to stabilize with the given physics options and are not included in analyses. This CCSM3 experiment has a horizontal resolution of approximately 1.4 degrees, 26 vertical levels, and 10 soil levels with output provided at 6-hour intervals.

The WRF Preprocessing System provides tools for defining a simulation domain, interpolating static data (e.g. orography, land use) to the domain, and converting and interpolating meteorological data to the domain. The process of initial conversion of the incoming boundary and initial condition data to a simple intermediate format is typically handled by the ungrib.exe program (Wang et al., 2011). The CCSM3 model output currently cannot be processed by the ungrib.exe program and so a program was developed to perform this task. The program reads the CCSM3 data and outputs intermediate data files containing the required variables for surface and sea-level pressure, atmospheric temperatures, winds, relative and specific humidity, sea ice, and soil temperature and moisture. Atmospheric variables were interpolated from the CCSM3 hybrid terrain-following and vertical pressure coordinates (sigma levels) to the vertical pressure coordinates required by WRF using the vertical interpolation techniques of Trenberth et al. (1993). The four soil layers required by the Noah land surface model (Chen and Dudhia, 2001)

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used by WRF were interpolated from the 10 soil layers in the CCSM3 output using weighted interpolation.

Preprocessing also includes the specification of sea-surface and lake temperatures. Sea-surface temperatures were prescribed using CCSM3 sea-surface temperatures at each 6-hour time step. Lake temperatures were computed using techniques based on average daily air temperature as described in the WRF Users Manual (Wang et al., 2011). In summary, lake temperatures are prescribed as the average air temperature based on CCSM3 surface air temperature for the lake grid point.

### 2.3 Physics options

Physics options utilized in the WRF simulations include Community Atmosphere Model version 3 (CAM3) short- and long-wave radiation scheme (Collins et al., 2004), MM5 Monin-Obukhov surface layer scheme (Skamarock et al., 2008), Yonsei University scheme (YSU) for the planetary boundary layer (Hong et al., 2006), Noah land surface model (Chen and Dudhia, 2001), WRF single-moment 6-class (WSM6) microphysics scheme (Hong and Lim, 2006), and the Kain-Fritsch cumulus parameterization (Kain and Fritsch, 1990).

The option `sst_update` was enabled in the WRF to provide time-varying sea-surface temperature, sea ice, albedo, and vegetation fraction values. The option `tmn_update` was enabled for updating deep soil temperatures. The specified boundary width was set to 10 cells. A radiation time step of 90 minutes was used. Although this afforded some savings in simulation runtime, the radiation time step is outside the recommended value of 1 minute per kilometer of resolution (e.g. 36 minutes for a 36-km resolution domain).

### 2.4 Validation

WRF estimates of air temperature at 2 meters and total precipitation were validated by comparison with PRISM output of monthly surface air temperature and total precipitation. PRISM output is available for

the conterminous United States at a 2.5 arc-minute spacing. PRISM output of minimum and maximum temperatures were averaged as an estimate of mean monthly temperature. Both WRF and PRISM output of mean monthly temperature and total precipitation were averaged over the Missouri, Yellowstone and James River watersheds for WY 2001–11. Note that WRF output is not expected to match the year-to-year trend because CCSM3 boundary conditions are not based on atmospheric observations; however, the range and variability in temperature and precipitation for WRF output should be analogous to PRISM output.

## 3. RESULTS

Although we used WRF to simulate climate across much of North America (fig. 1), applications of WRF results were focused on the Missouri, Yellowstone, and James River watersheds. Simulation results and validation of temperature and precipitation based on comparison with PRISM output are discussed for these three watersheds. Table 1 summarizes statistics for annual surface air temperature and precipitation from WRF and PRISM over the validation period.

Kendall's Tau test for non-parametrics (Conover, 1980) was used to determine the statistical significance of trends in annual temperature and precipitation. Kendall's Tau computes the correlation between the rank of values in a dataset with a monotonically increasing dataset. Positive correlation with monotonically increasing data would indicate an upward trend, whereas negative correlation would indicate a downward trend. A trend was considered to be statistically significant for a probability of  $\alpha = 0.05$  that the Kendall Tau value equals zero. Calculation of statistics was performed with the R statistical package (R Development Core Team, 2012). Results of Kendall's Tau for temperature and precipitation for each watershed from WRF model output are listed in table 2.

### 3.1 Missouri River Basin

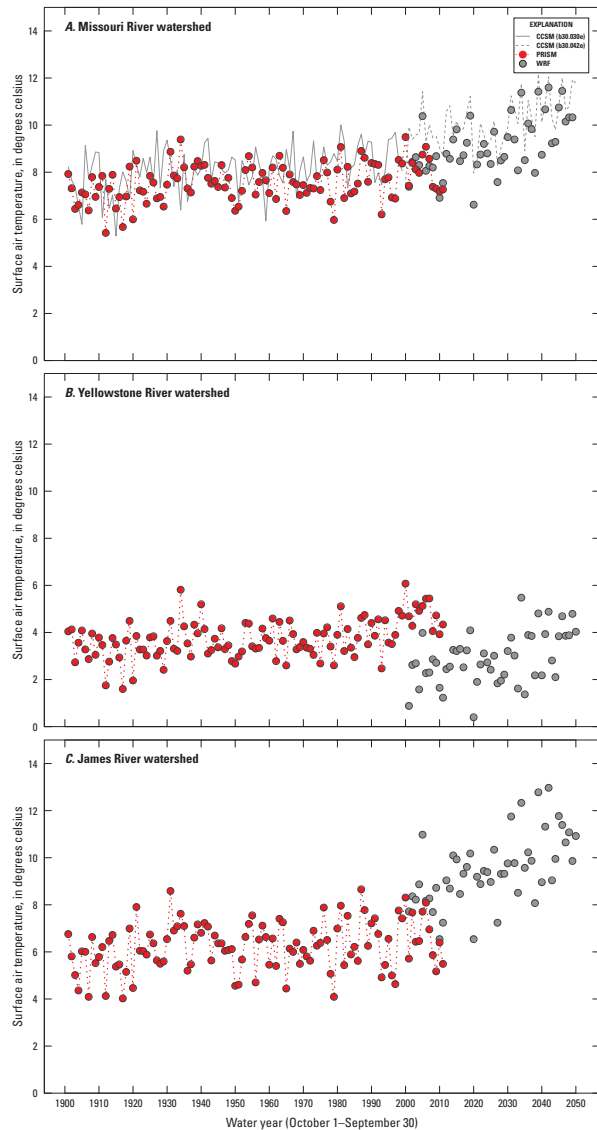
CCSM3 output compared to PRISM output for the Missouri River watershed are shown in Figures 2A

Temperature (degrees Celsius)	Missouri			Yellowstone			James		
	PRISM	WRF	Bias	PRISM	WRF	Bias	PRISM	WRF	Bias
Maximum	9.08	10.38	1.30	5.45	3.98	-1.47	8.09	10.98	2.89
Average	7.95	8.25	0.30	4.74	2.25	-2.49	6.54	8.25	1.71
Minimum	7.18	6.91	-0.27	3.93	0.88	-3.05	5.18	6.54	1.36
Standard Error	0.20	0.27		0.16	0.26		0.29	0.34	

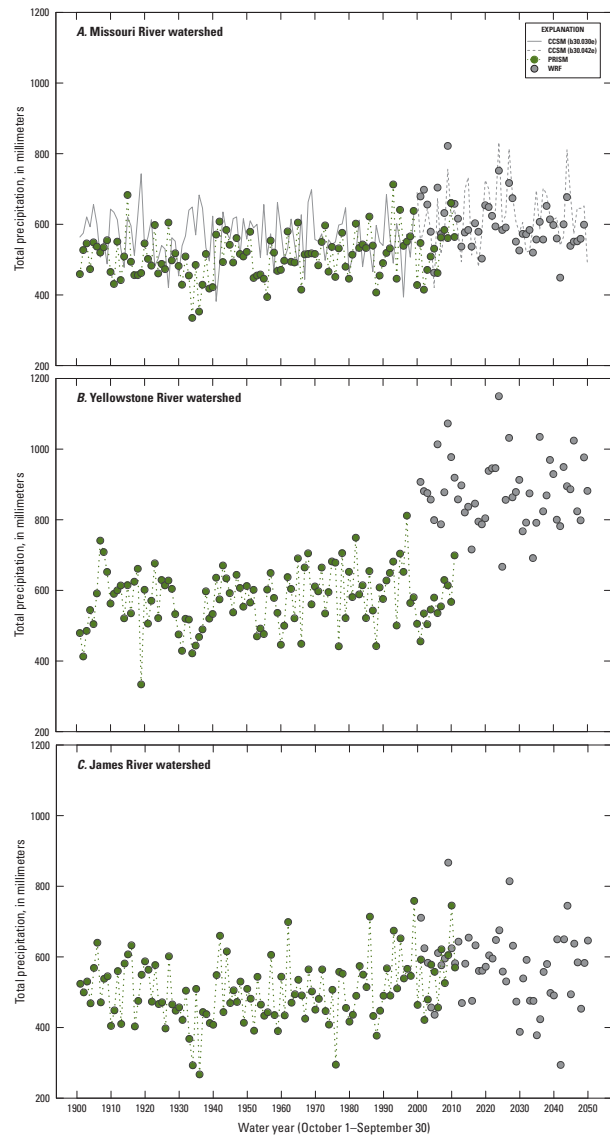
Precipitation (millimeters)	Missouri			Yellowstone			James		
	PRISM	WRF	Bias	PRISM	WRF	Bias	PRISM	WRF	Bias
Maximum	660	822	163	699	1073	374	745	867	121
Average	533	648	114	566	906	341	559	606	47
Minimum	415	463	48	456	787	332	421	436	15
Standard Error	20	27		20	26		27	35	

**Table 1.** Summary statistics of annual surface air temperature and precipitation for the Missouri, Yellowstone, and James River watersheds for water years 2001–11.



**Figure 2.** Surface air temperature for, A. Missouri River watershed, B. Yellowstone River watershed, and C. James River watershed for WY 2000–2050 (CCSM (b30.042e)), WY 1901–1999 (CCSM (b30.030e)), WY 1901–2011 (PRISM), and WY 2001–50 (WRF). CCSM output is only plotted for the Missouri River watershed.

and 3A. A CCSM3 climate experiment has three parts: pre-industrial climate of 1870, 20th Century Climate in Coupled Models (20C3M), and climate for a given emissions scenario. Climate of 1870 is simulated for 440 annual cycles. The 20C3M experiment continues the simulation from 1871 to 1999 based on observed CO<sub>2</sub> concentrations (experiment b30.030e). Climate is projected to 2100 using the A2 emissions scenario (experiment b30.042e). The CCSM3 experiments are described by Collins et al. (2006). Based on the Kendall's Tau test ( $p$ -value  $< 0.05$ ), both the CCSM3 and PRISM output for WY 1901–2011 had significant upward trends in temperature and no significant trend in precipitation.



**Figure 3.** Total precipitation for, A. Missouri River watershed, B. Yellowstone River watershed, and C. James River watershed for WY 2000–2050 (CCSM (b30.042e)), WY 1901–1999 (CCSM (b30.030e)), WY 1901–2011 (PRISM), and WY 2001–50 (WRF). CCSM output is only plotted for the Missouri River watershed.

CCSM3 exhibited a warm ( $+0.73\text{ }^{\circ}\text{C}$ ) and wet ( $+58\text{ mm}$ ) bias relative to PRISM output.

WRF model output compared to PRISM output for the Missouri River watershed for WY 2001–11 exhibits an average wet bias of 114 mm and an average warm bias of  $0.30\text{ }^{\circ}\text{C}$  (table 1). However, variability of temperature and precipitation from WRF and PRISM output are similar for this time period.

The projected climate from WRF model output for the Missouri River watershed has a significant ( $p$ -value  $< 0.05$ ; table 2) upward trend in temperature of  $2.5\text{ }^{\circ}\text{C}$  from WY 2001–50 (based on linear regression) and a significant ( $p$ -value  $< 0.05$ , table 2) upward trend in precipitation (fig. 2A, 3A).

Temperature	Missouri	Yellowstone	James
p-value	< 0.001	0.002	< 0.001
Z-score	4.207	3.137	4.493
Tau	0.415	0.306	0.439

Precipitation	Missouri	Yellowstone	James
p-value	0.022	0.987	0.252
Z-score	2.294	0.017	-1.146
Tau	0.227	0.002	0.112

**Table 2.** Results of Kendall's Tau test for significance of trends from WRF model output for the Missouri, Yellowstone, and James River watersheds for water years 2001–50.

### 3.2 Yellowstone River Watershed

WRF model output compared to PRISM output for the Yellowstone River watershed for WY 2001–11 exhibits an average wet bias of 341 mm and an average cold bias of 2.49 °C (table 1). Variability of temperature between WRF output and PRISM output are similar for this period, whereas precipitation shows greater variability in the WRF output.

The projected climate from WRF model output for the Yellowstone River watershed has a significant ( $p$ -value < 0.05) upward trend in temperature of 2.0 °C per from WY 2001–50 (based on linear regression) and no significant trend in precipitation (fig. 2B, 3B).

### 3.3 James River Watershed

WRF model output compared to PRISM output for the James River watershed for WY 2001–11 exhibits an average wet bias of 47 mm and an average warm bias of 1.71 °C (table 1). However, variability in temperature and precipitation from WRF and PRISM output are similar for this time period.

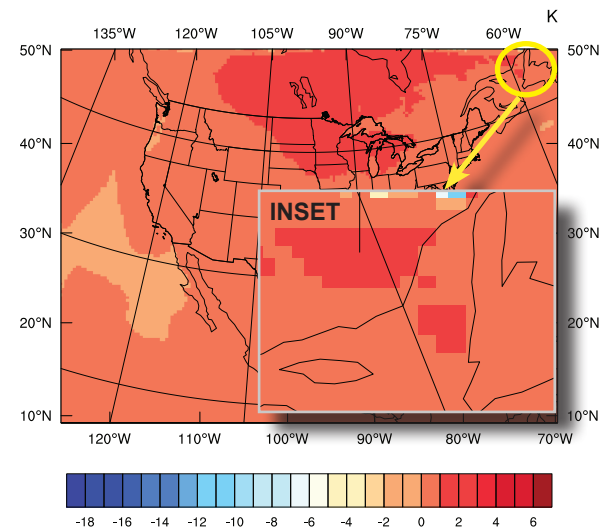
The projected climate (WY 2001–50) from WRF model output for the James River watershed has a significant ( $p$ -value < 0.05) upward trend in temperature of 3.0 °C from WY 2001–50 (based on linear regression) and no significant trend in precipitation (fig. 2C, 3C).

### 3.4 Radiation Time Step

The radiation time step is an important model configuration parameter that influences generation of precipitation. Additional sensitivity tests were performed with respect to the radiation time step for a 1-year period (WY 2001) to assess the effect this may have on longer term climate simulations. The WRF model was run with a modified radiation time step of 36 minutes for WY 2001 (WRF\_RADT36). This was compared with the WRF model output that used a radiation time step of 90 minutes (WRF\_RADT90). The average precipitation for WRF\_RADT36 output compared to WRF\_RADT90 output showed slight increases in convective, frontal, and total precipitation over the entire model domain. In contrast, average precipitation for WRF\_RADT36 output compared to WRF\_RADT90 output showed increased frontal precipitation, decreased convective precipitation, and decreased total precipitation for the Missouri River watershed.

### 3.5 Stability at Lateral Boundaries

Unstable solutions were observed at isolated points along the lateral boundaries that had high topographic gradients (fig. 4). The occurrence and effects of these problem points were minimized through careful selection of the domain boundaries. Avoiding areas with these topographic gradients is not always realistic.



**Figure 4.** Stability at lateral boundaries. Temperature range represents the average of the last 10 years of temperature at 2 meters minus the average of the first 10 years of temperature at 2 meters. The inset graphic shows an area along the lateral boundary where there are points of instability.

## 4. Discussion

WRF model output of surface air temperature and precipitation compared to PRISM output indicate the presence of bias. Possible sources of the bias observed in the WRF output include model configuration issues and bias in CCSM3 boundary conditions. Bias in CCSM3 has been noted in other studies such as Holland et al. (2010) who found that climate bias from CCSM simulations affected WRF simulations of cyclone climatology.

The relatively coarse radiation time step used for this simulation resulted in underproduction of frontal precipitation and more extreme convective precipitation events in the Missouri River watershed compared to the WRF\_RADT36 output for WY 2001. The results of decreasing the radiation time step highlighted the effect this parameter has on simulated precipitation.

## 5. Conclusion and Future Work

Here we have presented the results from a WRF regional climate model forced by CCSM3 output. Within the Missouri River watershed, the model output provides insight into predicted climate for the Yellowstone and James River watersheds that the CCSM model output was not designed to resolve. We identified possible problems with model configuration, input forcings, and model output to address in future simulations.

Future simulations of the WRF regional climate model will include an outer domain of 108 km that

matches CCSM elevations to eliminate the instabilities at lateral boundaries. Topography transitions to the WRF higher resolution topography for finer resolution nested domains. Additionally, reducing the radiation time step will improve representation of precipitation in the model. Results from the next simulation will be compared with the current model output to assess the long-term effects of the radiation time step over the entire model simulation.

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